

Using IXO For Cosmology Studies with Clusters

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Outline

Standard Cosmological Model

Observations of Clusters Can Test the Standard Model

Current Uncertainties in the Cluster Tests

An IXO Cluster Cosmology Program

Summary

Standard Cosmological Model

General Relativity + Six Parameters Describing Matter & Energy

Present Hubble parameter H_0

Present density of matter Ω_m

Present density of baryons Ω_b

Present fluctuations of matter in 8 Mpc spheres σ_8

Optical depth to last scattering τ

Initial matter fluctuation power spectrum index n_s

Model describes well the structure in and evolution of the universe

If GR is correct and there are really only six parameters, we are nearly done.

All but τ are currently measured at $\leq 5\%$ level.

X-ray Observations of Galaxy Clusters Played an Early Role in Establishing the Standard Model

Local cluster number density: evidence for low σ_8
(Henry & Arnaud ApJ 372, 410, 1991)

Cluster gas fraction: evidence for low Ω_m
(White et al. Nature 366, 429, 1993)

Goal is to test standard model

Is the dark energy density $\Omega_{\Lambda} = 1 - \Omega_m$?
Flat universe?

Is the dark energy a cosmological constant?
Equation of state parameter $w_0 = -1$?
Equation of state parameter constant? ($w_a = 0$)

Is dark energy only an artifact of General Relativity not being correct on Mpc scales?

Tests are of two general types

Growth of structure

Measures growth factor $D(z)$

cluster $n(z)$, weak lensing shear, redshift distortions

Geometrical using standard quantities

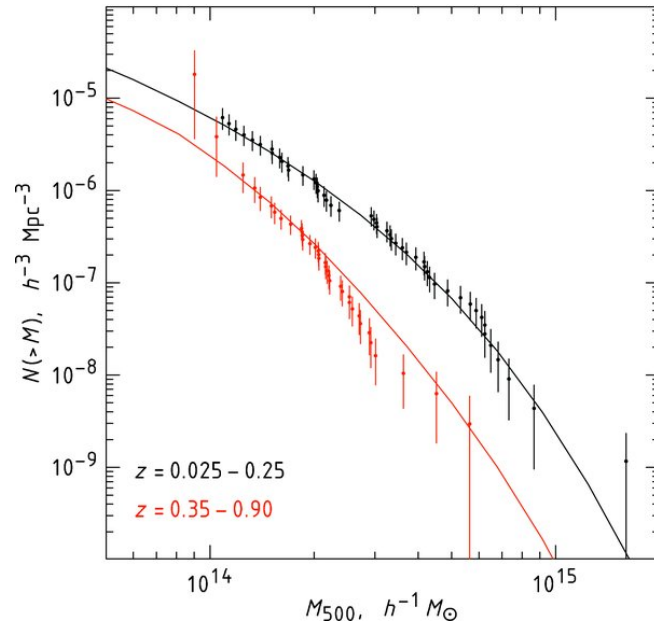
Measures distance $d(z)$

cluster $f_{gas}(z)$, CMB, BAO, SNIa

General Relativity test compares results of the two

State of art cluster tests are competitive with other methods

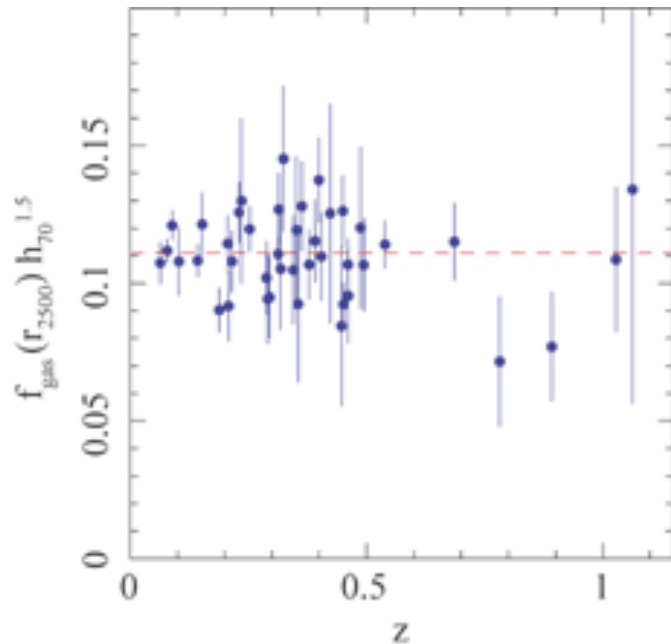
X-ray Cluster Cosmology State of the Art



Growth of Structure

Vikhlinin et al. ApJ 692, 1060, 2009

Cluster mass function at 2 epochs
86 clusters



Geometrical

Allen et al. MNRAS 383, 879, 2008

$f_{\text{gas}} - z$
42 clusters

IXO goal: increase sample size by x10

Uncertainties in Growth of Structure Test

What We Want To Do

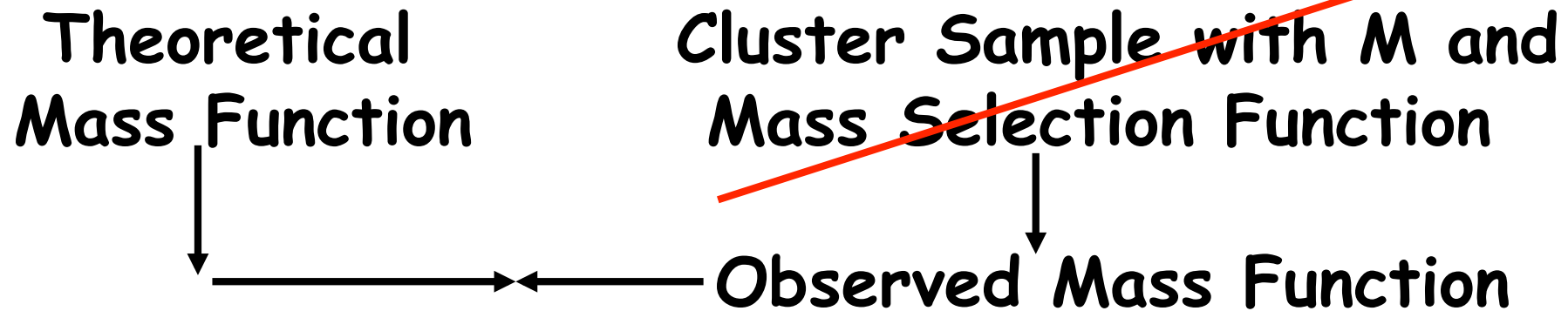
Theoretical
Mass Function

Cluster Sample with M and
Mass Selection Function



Uncertainties in Growth of Structure Test

What We Want To Do

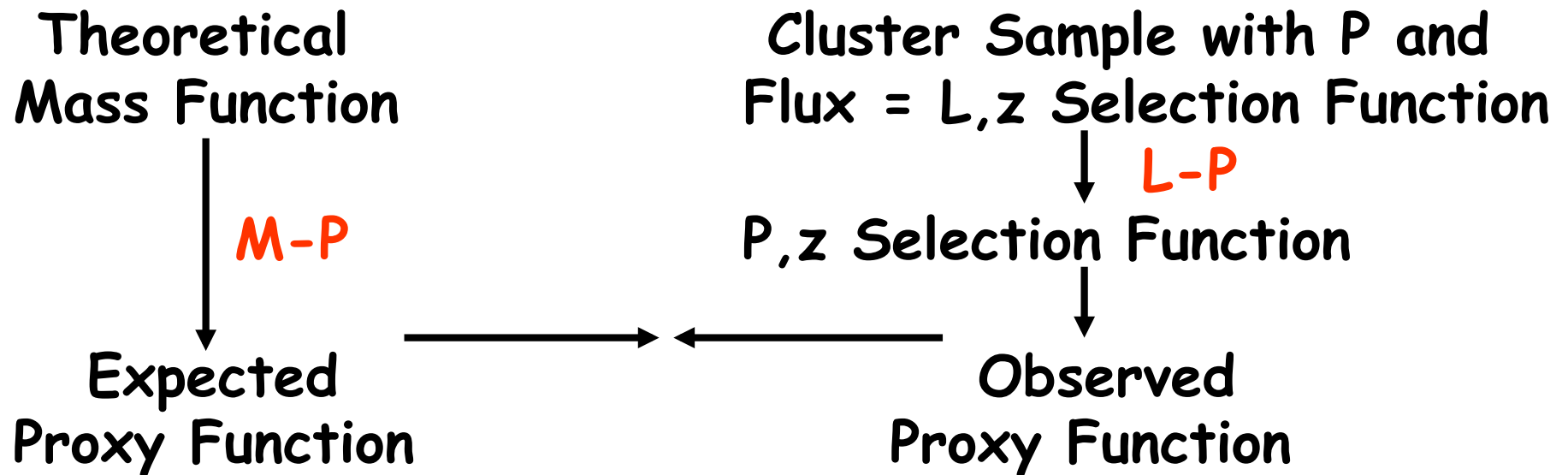


There are no mass selected samples, only flux selected. Can only measure luminosity function without additional information.

Luminosity is a low-fidelity mass proxy, so luminosity function much less constraining than mass function. Use a higher fidelity proxy (P).

Uncertainties in Growth of Structure Test

What We Actually Do



Cosmological Information Comes From:

Mass Function, M-P, L-P, L,z Selection Function

Baryon Physics introduces scatter in M-P, L-P

Uncertainties in Growth of Structure Test

Must find an easily observable low-scatter proxy and
Calibrate the form of and scatter in M - P , L - P relations

Minimum number of parameters: $3 + 3 = 6$

If nonzero redshift $\times 2 \quad \times 2 = 12$

Plus errors on all of the above 24

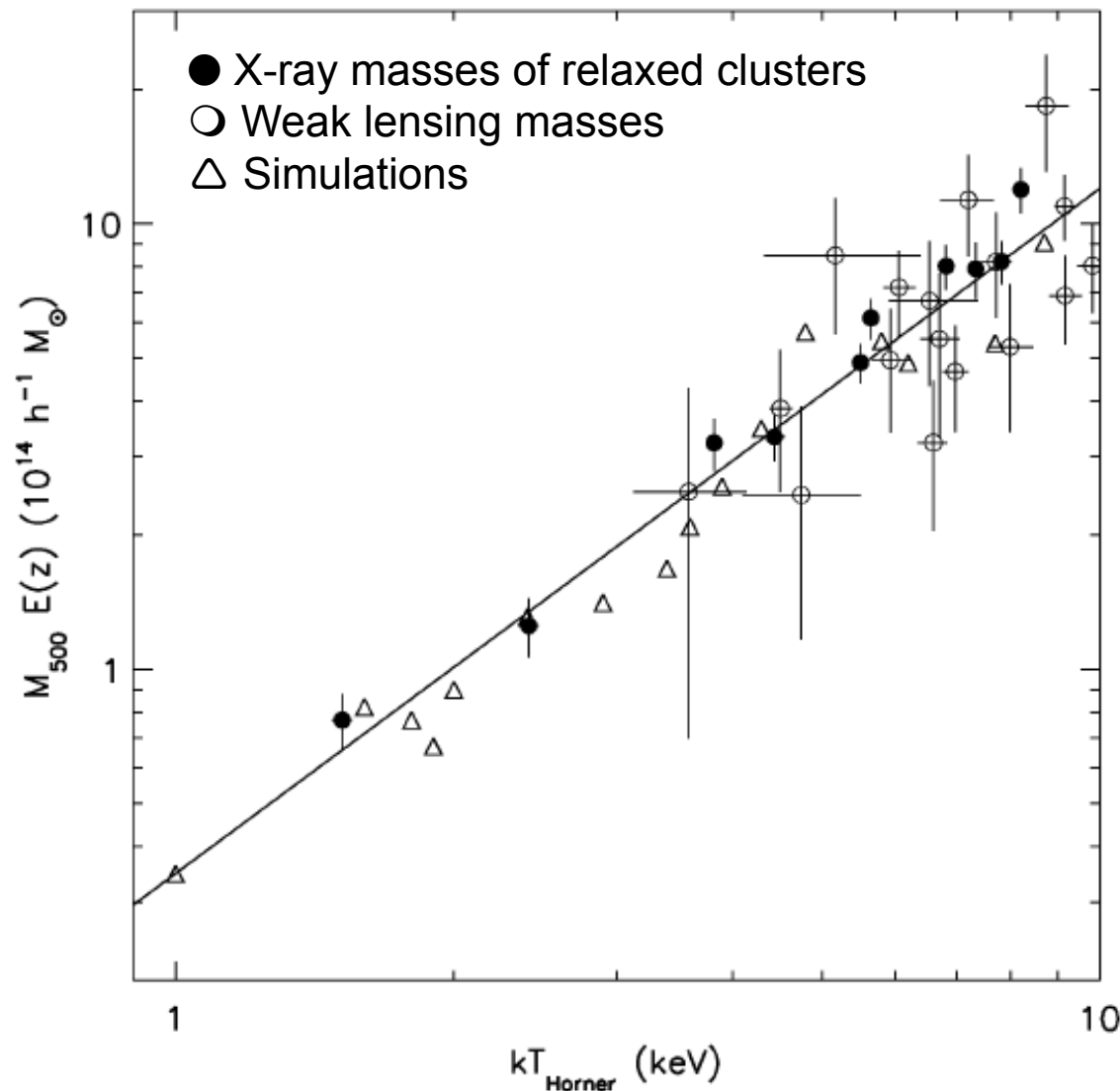
Proxies used: L , kT , M_{gas} , $Y_x = M_{\text{gas}} \times kT$

Scatter of $M - P$ for last 3 are $\sim 10\%$.

Scatter of L can be reduced if core excised, but not possible at all redshifts

Biggest uncertainty now. Very little known at $z > 0.3$

M – T from Three Methods



First time all three
methods agree

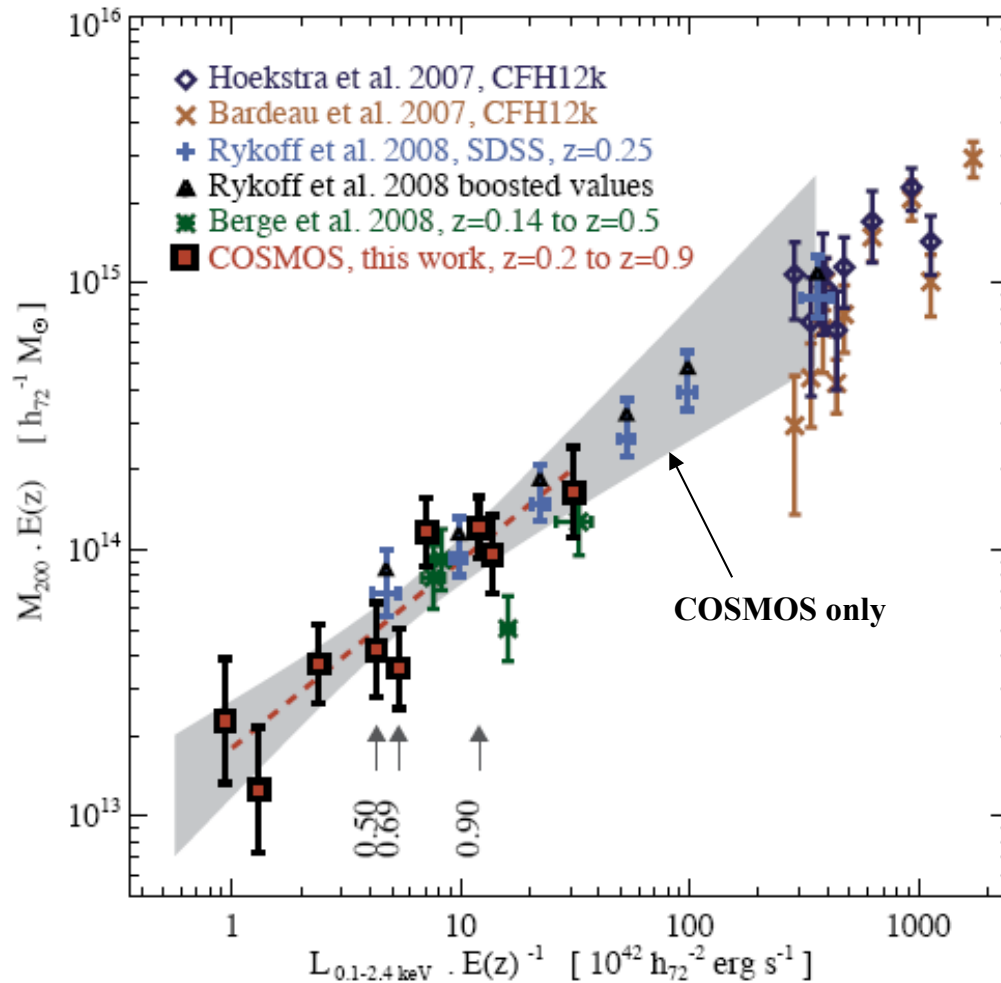
Suggests convergence
to true relation

$z < 0.3$ only

Note errors on X-ray
masses < WL masses

Henry et al. ApJ 697, 1128, 2009

M – L from Weak Lensing Masses



Slope disagrees
with self-similar

Evolution assumed
to be self-similar
(Why given above?)

Scatter hard to
measure because
of stacked WL
masses and large
errors

Leauthaud et al. ApJ 709, 97, 2010

Uncertainties in f_{gas} Geometrical Test

Can the Total Mass be Measured to Few %?

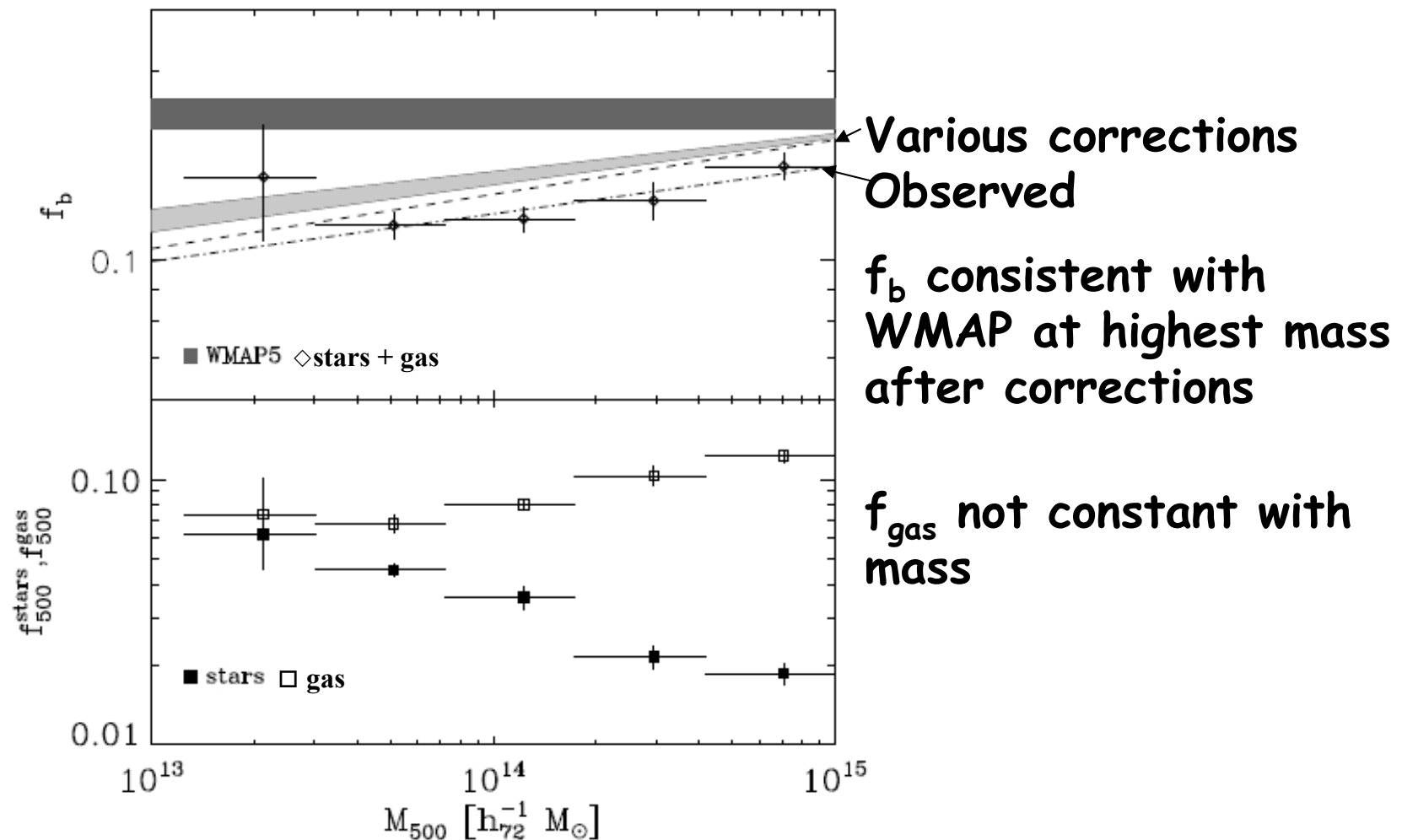
Pick relaxed looking clusters and assume hydrostatic equilibrium.

Surely some non-pressure support at few % level from

- bulk motions
- turbulence
- cosmic rays
- magnetic fields

Overcome this uncertainty on average with weak lensing masses?

Uncertainties in f_{gas} Geometrical Test Are Cluster Baryon Fractions Really Standards?



Giodini et al ApJ 703, 982, 2009

Cluster Samples

	Now	IXO Epoch Goal
$z < 1$	~ 1000	1000
$z > 1$	~ 10	1000

Where will the new high z clusters come from?

eROSITA, WFXT

SZ surveys: SPT, ACT, Planck

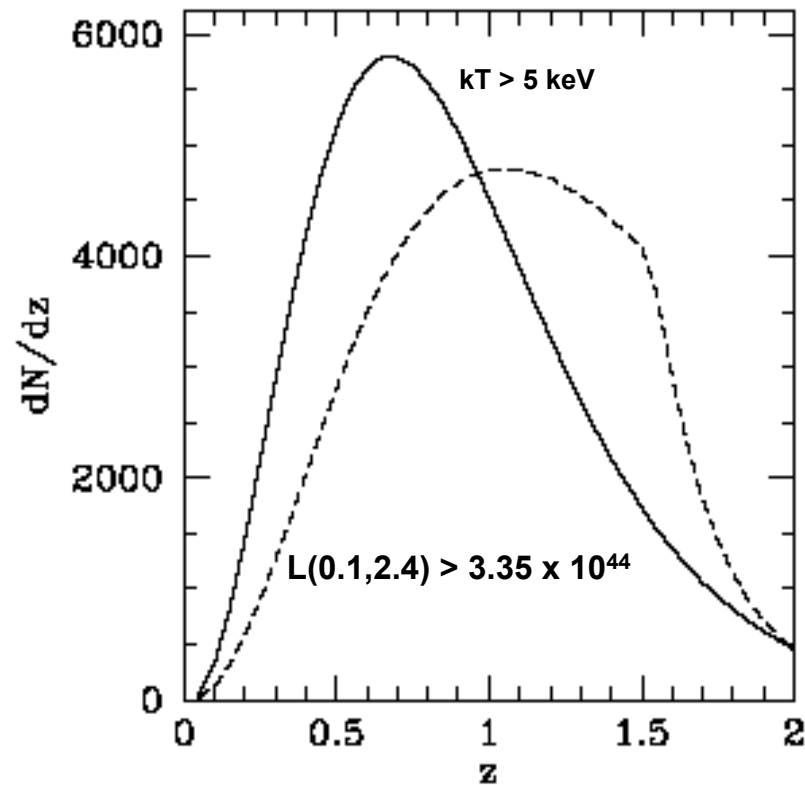
IXO itself

Where will the new redshifts come from?

A very good question.

Spectroscopic redshift of one $z \sim 2$ cluster can take 4 hours of 8m telescope time. We want 100s! X-ray spectroscopy? Photo z ?

Redshift Distributions from eROSITA Survey



Rapetti et al. MNRAS 388, 1265, 2008

IXO Program for Growth of Structure Test

Goal is ~1% measurement of normalization of $n(M,z)$ to $z \sim 2$

Vikhlinin et al. arXiv 0903.2297

Want $n(M)$ from 100 clusters in 20 $\Delta z = 0.1$ shells $z = 0-2$

Want M to few %

Measure M_{gas} , kT , Y_x in X-rays: high precision but biased

1000 $z < 0.8$ clusters from eROSITA

1000 $z > 0.8$ clusters X 15 ks from IXO

Measure weak lensing masses for all: low precision but unbiased
vs ~100 today

IXO = 15 Ms

IXO Program for f_{gas} Geometrical Test

Rapetti et al. MNRAS 388, 1265, 2008

4000 kT > 5 keV clusters X 1 ks snapshot to find relaxed objects

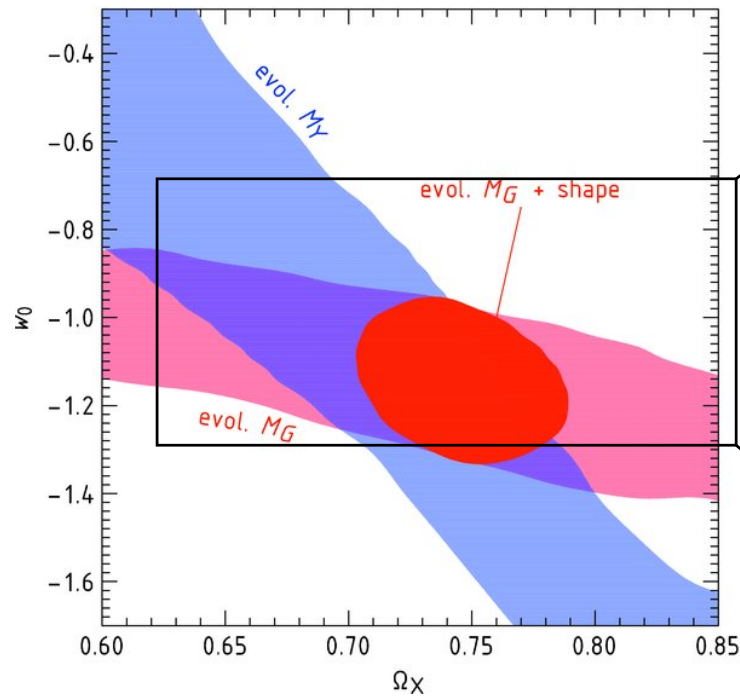
500 relaxed clusters X 20 ks to measure M_{gas} , M_{tot} , f_{gas}

IXO = 14 Ms

Cluster Cosmology Grand Total < 20 Ms (? overlap)

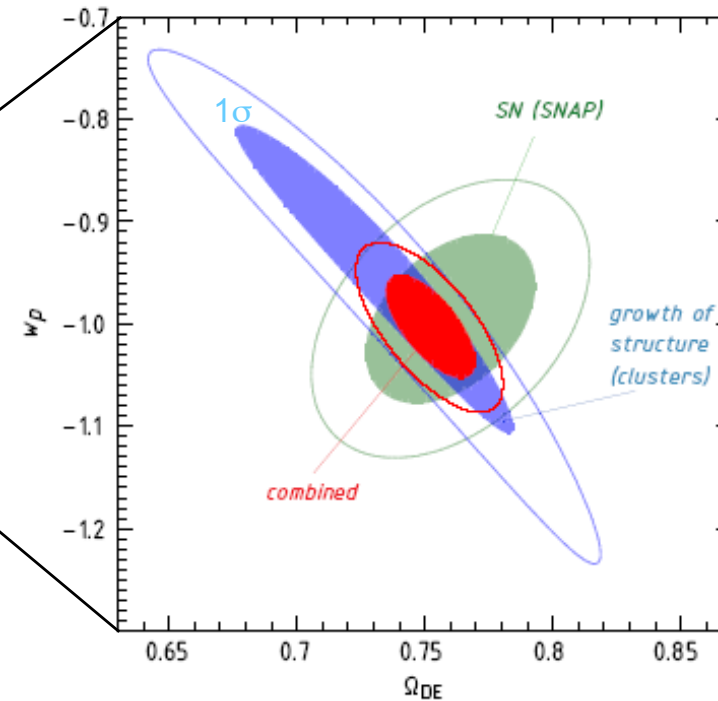
Improvement on Constraints: Growth of Structure

Now



Vikhlinin et al. ApJ 692, 1060, 2009

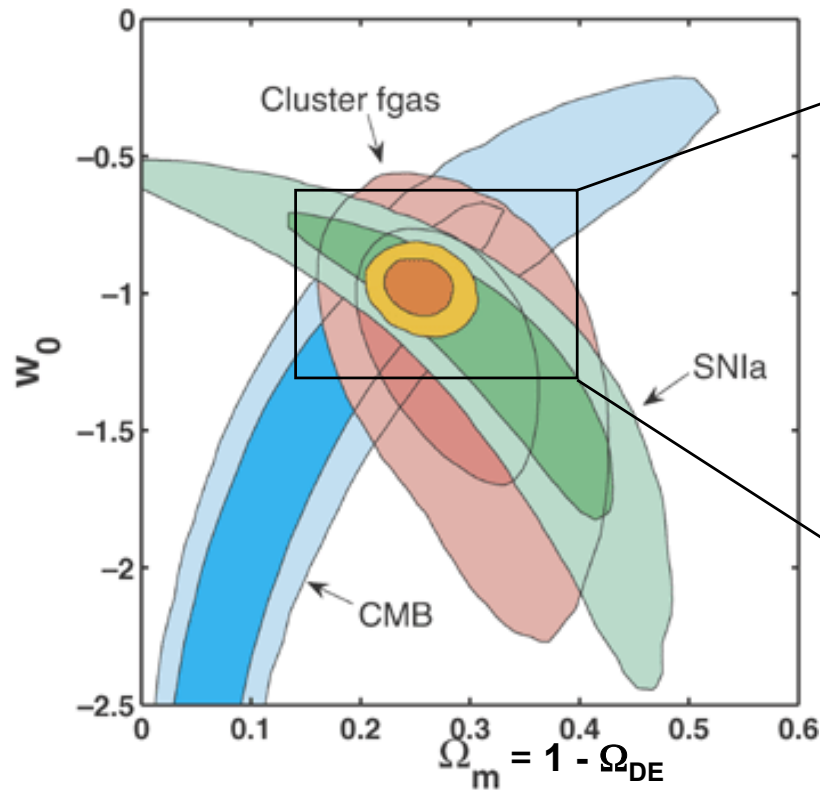
IXO Epoch



Vikhlinin et al. 0903.2297

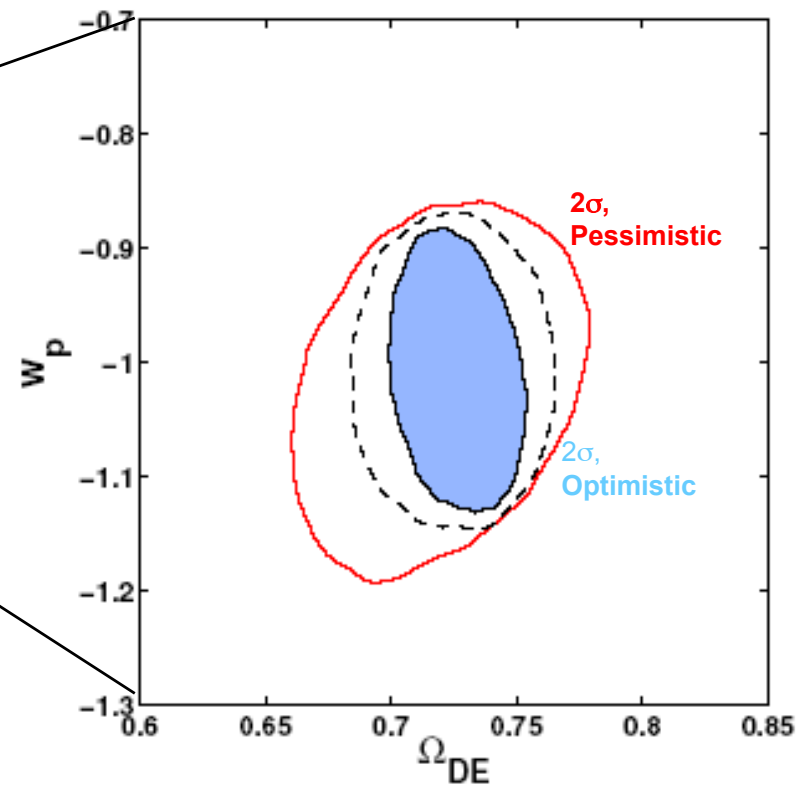
Improvement on Constraints: f_{gas}

Now



Allen et al. MNRAS 382, 879, 2008

IXO Epoch



Rapetti et al. MNRAS 388, 1265, 2008

Testing General Relativity

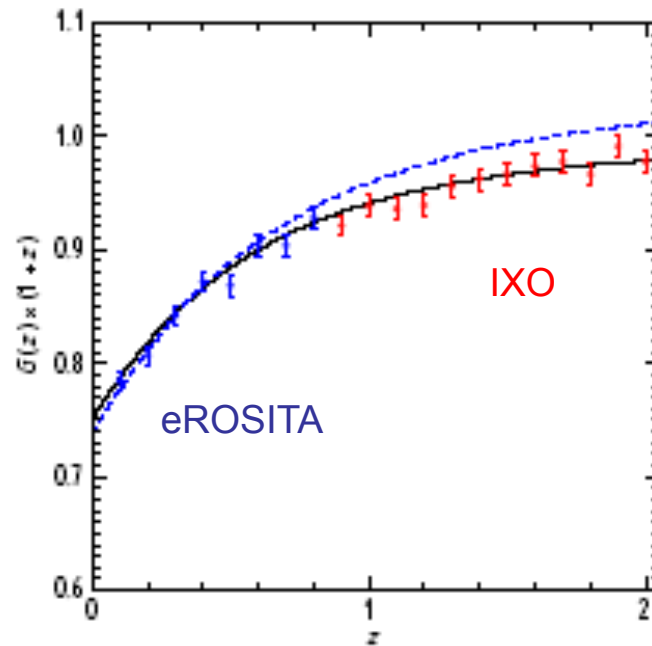
Equation of GR $G_{\mu\nu} = 8\pi T_{\mu\nu} = 8\pi(T^M_{\mu\nu} + T^{\text{DE}}_{\mu\nu})$

Schematically $G_{\mu\nu} - 8\pi T^{\text{DE}}_{\mu\nu} = 8\pi T^M_{\mu\nu}$
New Gravity No dark energy

Some Non-GR theories can have the same $d(z)$ as GR, which means they can not be distinguished by CMB, BAO or SNIa observations.

Difference is growth of structure between $z = 1100$ when CMB is formed and $z = 0$. For the two NGR theories that are well developed, the difference in σ_8 is $\sim 5\%$, so must measure σ_8 to $\sim 1\%$.

Growth Factor for standard model and DGP NGR model



~5% difference

Vikhlinin et al. arXive 0903.2297

Improvement on Constraints: Testing GR

Now

Consistent with GR

Inconsistent with non-GR at low confidence

DGP $< 2\sigma$ (Rapetti et al., 0911.1787)

$f(R) < 1\sigma$ (Reyes et al., Nature 464, 256, 2010)

IXO Epoch

Discriminate between GR and DGP at $6-7\sigma$

Between GR and other TBD models at similar level

Summary

Standard model has been verified to percent level.

Still very unsatisfying since almost all of the universe consists of dark stuff.

IXO observations of clusters can make precise tests of standard model.

Before doing so will need:

- Very large cluster sample to $z \sim 2$

- Redshift estimates for thousands of $z > 1$ clusters

- Weak lensing masses for thousands of clusters

Will need the time until IXO launch!